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Laser Hazard Analysis For Various Candidate Diode Lasers Associated With The High Resolution Pulsed Scanner

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Laser Hazard Analysis For Various Candidate Diode Lasers Associated With The High Resolution Pulsed Scanner

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Abstract

A laser hazard analysis and safety assessment was performed for each various laser diode candidates associated with the High Resolution Pulse Scanner based on the ANSI Standard Z136.1-2000, American National Standard for the Safe Use of Lasers. A theoretical laser hazard analysis model for this system was derived and an Excel© spreadsheet model was developed to answer the "what if questions" associated with the various modes of operations for the various candidate diode lasers.

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High Resolution Pulsed Scanner

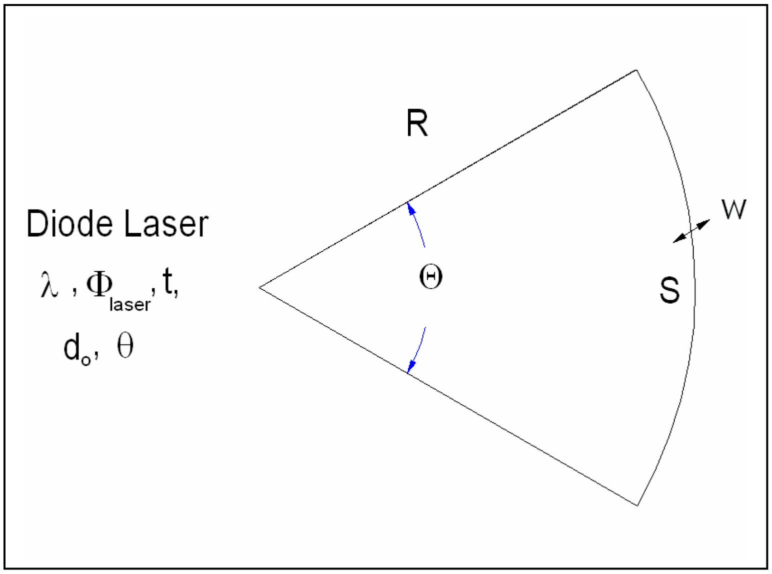

Figure 1

Schematic of the diode laser output geometry

I. Overview

The high-resolution laser scanner laser output beam geometry is spread out over a fan angle (Θ). The beam width (w) is less than the limiting aperture ($d_{\lim}$) at the minimum radial distance from the laser (R) that can be accessed by personnel. This distance is controlled by an engineered enclosure. The diode laser is expected to operate at one of two possible pulse repetition rates (*PRF*). The CW diode laser is computer controlled and is to be pulsed "on" for either 1 microsecond or 10 microseconds at the selected PRF. The laser diode is expected to operate at the highest allowed output power (pulsed), to achieve the highest signal to noise ratio, and still be "eye safe" for unrestricted use with the general public.

II. Configuration

The radiant energy (Q_o) exiting the diode laser is assumed to be uniformly loaded into the arc surface area referred to as the **scan area** (A_{scan}) at the radial distance (R). This scan area, at radial distance (R), can be expressed as the product of the arc length (S) and the beam width (w).

$$A_{scan} = S \cdot w$$

Transmitted Radiant Energy

The radiant energy transmitted through the limiting aperture $\left(Q_{\lim}\right)$ can be expressed as being directly proportional to the diode laser radiant output and the ratio of the transmitted area $\left(A_\tau\right)$ to the scan area $\left(A_{scan}\right)$.

$$Q_{\lim} \sim Q_{laser}\left(\frac{A_\tau}{A_{scan}}\right)$$

1st Order Approximation

When a laser beam dimension is less than the limiting aperture ($d_{\lim}$) the limiting aperture is treated as that beam dimension [*ANSI Std. Z136.1-2000 (9.2.2.1)*]. In the case where the beam width (*w*) is less than the limiting aperture diameter the radiant energy transmitted through the limiting aperture $\left(Q_{\lim}\right)$ is a function of the radiant energy output of the laser $\left(Q_{laser}\right)$, the ratio of the limiting aperture ($d_{\lim}$) to the arc length (*S*). This first order approximation will yield a higher transmitted radiance, giving rise to a conservative safety bias. It is assumed that the radiant energy is distributed uniformly over this area.

$$Q_{\lim} \sim Q_{laser}\left(\frac{d_{\lim}}{S}\right)$$

The arc (surface) length is a function of the fan angle and the radial distance and can be expressed as:

$$S = \Theta \cdot R \qquad \text{Where } \Theta \text{ is in radians}$$

$$S = \Theta \cdot \left(\frac{\pi}{180^\circ}\right) \cdot R \qquad \text{Where } \Theta \text{ is in degrees}$$

For the radiant exposure to be "eye safe" the radiant energy transmitted through the limiting aperture should be equal to or less than the Class 1 Allowable Emission Limit (*AEL*) for invisible wavelengths and equal to or less than the Class 2 AEL for visible wavelengths. The maximum allowed eye safe energy transmitted ($Q_{\lim-\max}$) is:

$$Q_{\lim-\max} = Class\ 1\ \ AEL_{invisible}$$

or

$$Q_{\lim-\max} = Class\ 2\ \ AEL_{visible}$$

For the maximum “eye safe” condition to exist, the maximum radiant energy transmitted through the limiting aperture is set equaled to the AEL.

$$AEL = Q_{laser}\left(\frac{d_{\lim}}{S}\right)$$

Therefore, the diode laser, maximum radiant output energy allowed for the “eye safe” condition is:

$$Q_{laser} = AEL\left(\frac{S}{d_{\lim}}\right)$$

$$Q_{laser-\max} = AEL\left(\frac{\Theta \cdot \left(\frac{\pi}{180^{\circ}}\right) \cdot R}{d_{\lim}}\right)$$

Where;

$Q_{laser-\max}$:	The diode laser maximum radiant output for eye safe operation.
AEL:	The appropriate Allowable Emission Limit.
Θ:	Fan angle (in degrees)
$d_{\lim}$:	Limiting aperture (cm).
R:	Radial distance of the engineering control barrier (cm).

III. Hazard Analysis

The maximum permissible exposure (*MPE*) for a repetitively pulsed laser is always the smallest of the MPE values determined from the application of the ANSI Rule 1 through ANSI Rule 3 [*ANSI Std. Z136.1-2000 (8.2.3)*].

For all PRF(s) less than the critical frequency ANSI Rule 2 does not apply [*ANSI Std. Z136.1-2000 (8.2.3.2)*]. The critical frequencies are 55 KHz for the wavelength range 400 nm to 1050 nm and 20 KHz for the wavelength range 1050 nm to 1400 nm [*ANSI Std. Z136.1-2000 (8.2.3.2-Note)*].

Assuming a uniform multi-pulse exposure greater than 1 nanosecond the ANSI Rule 1 MPE will always be greater than the ANSI Rule 3 MPE and will not be applicable.

The appropriate MPE for a uniform multiple pulse exposure is derived from ANSI Rule 3.

$$MPE_{rule3} = C_p \cdot MPE_{rule1}$$

The correction coefficient (C_p) a multiple pulse exposure is given in *Table 6* of *ANSI Std. Z136.1-2000*.

$$C_p = n^{-0.25}$$

The number of pulses in the exposure is a function of the PRF and the appropriate exposure (T).

$$n = PRF \cdot T$$

The **multiple pulse correction** can be expressed as:

$$C_p = \left(PRF \cdot T\right)^{-0.25}$$

The ANSI Rule 3 MPE can then be express as:

$$MPE_{rule3} = \left(PRF \cdot T\right)^{-0.25} \cdot MPE_{rule1}$$

The Allowable Emission Limit is defined as the product of the appropriate MPE and the area of the limiting aperture [*ANSI Std. Z136.1-2000 (3.2.3.4.1(2))*]:

$$AEL \equiv MPE \cdot A_{\lim}$$

$$AEL = MPE \cdot \left[\frac{\pi}{4} \left(d_{\lim} \right)^2 \right]$$

$$AEL = \left[\left(PRF \cdot T \right)^{-0.25} \cdot MPE_{rule1} \right] \cdot \left[\frac{\pi}{4} \left(d_{\lim} \right)^2 \right]$$

Recalling that the maximum diode laser energy was expressed as:

$$Q_{laser-\max} = AEL \left(\frac{\Theta \cdot \left(\frac{\pi}{180^\circ} \right) \cdot R}{d_{\lim}} \right) \qquad \text{(Page 7)}$$

The maximum "eye-safe" diode laser output energy can be expressed as:

$$Q_{laser-\max} = \left\{ \left[\left(PRF \cdot T \right)^{-0.25} \cdot MPE_{rule1} \right] \cdot \left[\frac{\pi}{4} \left(d_{\lim} \right)^2 \right] \right\} \left(\frac{\Theta \cdot \left(\frac{\pi}{180^\circ} \right) \cdot R}{d_{\lim}} \right)$$

$$Q_{laser-\max} = \left\{ \left[\left(PRF \cdot T \right)^{-0.25} \cdot MPE_{rule1} \right] \cdot \left[\frac{\pi}{4} \left(d_{\lim} \right) \right] \right\} \left(\Theta \cdot \left(\frac{\pi}{180^\circ} \right) \cdot R \right)$$

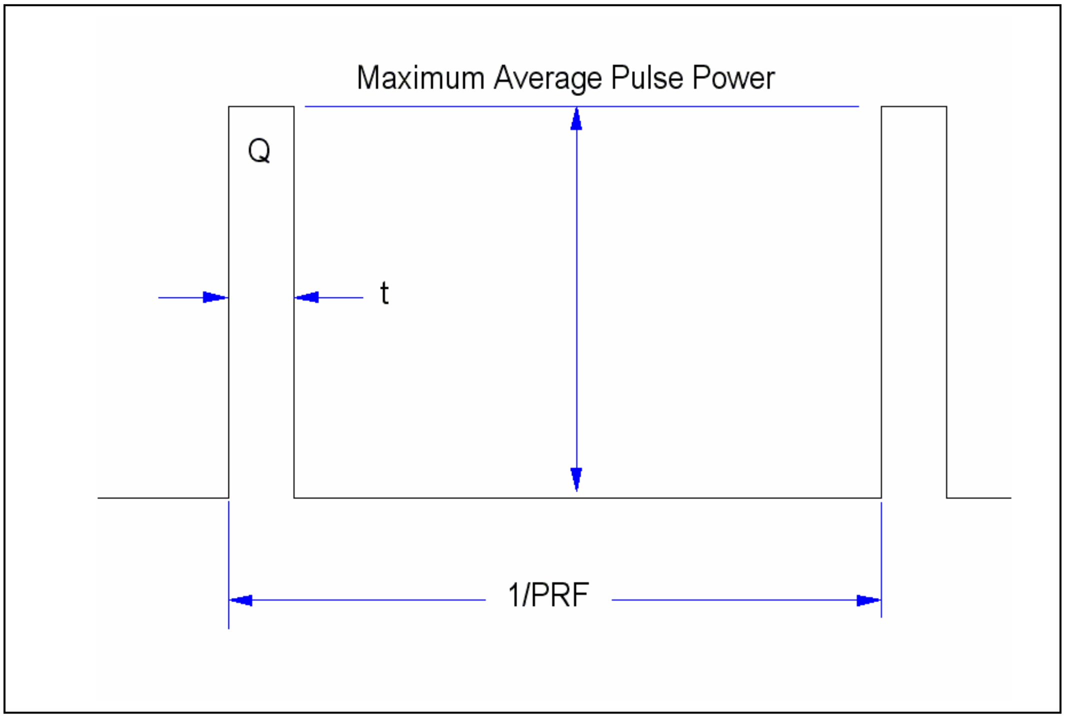

Figure 2

The diode laser maximum average radiant power for "**eye-safe**" operation can be expressed as a function of the maximum "eye-safe" pulse energy and the pulse exposure duration (figure 2).

$$\overline{\Phi}_{laser-\max} = \frac{\left\{\left[(PRF \cdot T)^{-0.25} \cdot MPE_{rule1}\right] \cdot \left[\frac{\pi}{4}(d_{\lim})\right]\right\}\left(\Theta \cdot \left(\frac{\pi}{180^{\circ}}\right) \cdot R\right)}{t}$$

Where:

$\overline{\Phi}_{laser-\max}$:	Maximum average (CW) diode laser power (watts)
PRF :	Pulse repetition frequency (sec^{-1}).
T :	Appropriate exposure [*ANSI Std. Z136.1-2000 (Table 4a)*].
MPE_{rule1} :	ANSI Rule 1 MPE [*ANSI Std. Z136.1-2000 (Table 5a)*].
$d_{\lim}$:	Limiting aperture [*ANSI Std. Z136.1-2000 (Table 8)*].
Θ :	Fan angle (degrees).
R :	Radial distance from the diode laser (cm).
t :	Pulse duration (computer controlled).

IV. Hazard Evaluations of Various Candidates

A. Visible Laser Diode (= 670 nm)

Given conditions:

PRF :	30 $\sec^{-1}$
T :	0.25 sec (Class 2 Hazard consideration)
$d_{\lim}$:	0.7 cm
Θ :	45 degrees
R :	60 cm
t :	1 microsecond

The appropriate ANSI Rule 1 MPE is given in *ANSI Std. Z136.1-2000 (Table 5a)*.

$$MPE_{rule1} = 500 \times 10^{-9} \; {}^{J}\!/\!_{cm^2} \qquad 400 \;\; nm \le \lambda \le 700 \;\; nm$$

$$1 \times 10^{-9} \sec \le t \le 18 \times 10^{-6} \sec$$

The maximum average CW radiant power for "eye safe" operation of the laser diode for the given configuration can be evaluated as follows:

$$\overline{\Phi}_{laser-\max} = \frac{\left\{\left[\left(30 \sec^{-1} \cdot 0.25 \sec\right)^{-0.25} \cdot 500 \times 10^{-9} \; {}^{J}\!/\!_{cm^2}\right] \cdot \left[\frac{\pi}{4}\left(0.7 cm\right)\right]\right\}\left(45^\circ \cdot \left(\frac{\pi}{180^\circ}\right) \cdot 60 cm\right)}{1 \times 10^{-6} \sec}$$

$$\overline{\Phi}_{laser-\max} = 7.83 \;\; watts$$

An Excel Spreadsheet was used to model the high-resolution pulse scanner to quickly analyze various diode candidates and various operational conditions are presented in Table 1 & 2.

B. Infrared Laser Diode (= 810 nm)

Given conditions:

PRF :	30 sec^{-1}
T :	10 sec (Class 1 Hazard consideration)
$d_{\lim}$:	0.7 cm
Θ :	45 degrees
R :	60 cm
t :	1 microsecond

The appropriate ANSI Rule 1 MPE is given in *ANSI Std. Z136.1-2000 (Table 5a).*

$$MPE_{rule1} = 5 \cdot C_A \times 10^{-7}\ {}^{J}\!/_{cm^2} \qquad 700\ \ nm < \lambda < 1050\ \ nm$$

$$1 \times 10^{-9} \sec \le t \le 18 \times 10^{-6} \sec$$

The wavelength correction coefficient (C_A) is listed in *ANSI Std. Z136.1-2000 (Table 6).*

$$C_A = 10^{2(\lambda - 0.7)} = 10^{2(0.81 - 0.7)}$$

$$C_A = 10^{0.22}$$

$$MPE_{rule1} = 5 \cdot \left(10^{0.22}\right) \times 10^{-7}\ {}^{J}\!/_{cm^2}$$

Evaluation of the maximum average CW radiant power of “eye safe” operation of the laser diode for this configuration can be evaluated as follows:

$$\overline{\Phi}_{laser-\max} = \frac{\left\{\left[\left(30\sec^{-1} \cdot 10\sec\right)^{-0.25} \cdot \left(5 \cdot \left(10^{0.22}\right) \times 10^{-7}\ {}^{J}\!/_{cm^2}\right)\right] \cdot \left[\frac{\pi}{4}\left(0.7cm\right)\right]\right\}\left(45^\circ \cdot \left(\frac{\pi}{180^\circ}\right) \cdot 60cm\right)}{1 \times 10^{-6} \sec}$$

$$\overline{\Phi}_{laser-\max} = 5.17\ \ watts$$

V. Conclusion

Table 1 summarizes the maximum average diode laser radiant output power allowed at a 30 hertz PRF for a fan angle of 45 degrees and a radial distance of 60 centimeters for "eye safe" operations.

<u>Table 1</u>

Maximum "Eye Safe" Average Diode Laser Radiant Output Power (30 Hz, 45-Degree Fan Angle, 60 cm)

Wavelength (nm)	Pulse Duration 1 microsecond	Pulse Duration 10 microsecond
670	**7.83 watts**	**738 mw**
780	**4.50 watts**	**450 mw**
810	**5.17 watts**	**517 mw**

Table 2 summarizes the maximum average diode laser radiant output power allowed at a 60 hertz PRF for a fan angle of 45 degrees and a radial distance of 60 centimeters for "eye safe" operations.

<u>Table 2</u>

Maximum "Eye Safe" Average Diode Laser Radiant Output Power (60 Hz, 45-Degree Fan Angle, 60 cm)

Wavelength (nm)	Pulse Duration 1 microsecond	Pulse Duration 10 microsecond
670	**6.58 watts**	**658 mw**
780	**3.45 watts**	**345 mw**
810	**4.34 watts**	**434 mw**

VI. References

ANSI Std. Z136.1-2000, American National Standard for the Safe Use of Lasers

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